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Abstract: *The development of roller-compacted concrete (RCC) in the 1980's spurred a resurgence in the design and construction of stepped spillway chutes worldwide. New designs have stretched the limits on head and specific discharges, resulting in renewed discussions of cavitation potential. The uncertainty of cavitation formation and possible damage has led to conservative design approaches to limit specific discharge and include forced aeration ramps.*

Atmospheric and reduced-pressure modelling were performed at the Bureau of Reclamation's Denver laboratory on a sectional model of a stepped spillway for two channel slopes and one step height. Extensive measurements were used to characterize basic parameters such as friction factor, mean flow and time-averaged turbulence properties as well as the incipient cavitation index. The results show that cavitation can form in nonaerated flows on stepped spillways and the incipient cavitation index is related to the friction coefficient C_f of these uniformly distributed macro-roughness elements.

Keywords: *stepped spillway, cavitation, friction coefficient, macro-roughness.*

1. INTRODUCTION

The design of stepped spillways has been the topic of many research studies and publications over the past 30 years. Researchers have used new measurement techniques and instrumentation such as air concentration probes and particle image velocimetry (PIV) to quantify aeration properties and energy dissipation characteristics of stepped chutes and provide more details for design purposes and new applications.

The energy dissipation benefit of a stepped versus a smooth chute has been documented many times over (Chanson [2001], Hunt and Kadavy [2008], Miereles and Matos [2009]). Their use has become common on low head structures and they have performed well in many locations for many years. Their use in high-head spillways or with large specific discharges has still been somewhat limited. Cavitation potential, especially with the combination of deep flows and high velocities has been addressed by many researchers. No public evidence exists that a stepped chute has experienced cavitation damage. Most high-head structures that have been constructed to date feature steep stepped chutes (50- to 60-degrees) and relatively small specific discharges, resulting in fully aerated flow conditions. However, a new design is pushing the current design principles.

A new spillway at Folsom Dam near Sacramento, California, USA is currently under construction. The control structure features 5 top-seal tainter gates, with a maximum head of slightly over 30.5 m. The gates discharge onto a 640 m-long by 51.5 m-wide smooth chute with a slope of 0.02. The chute then begins a parabolic transition to a constant slope of 0.4025. Through the parabolic transition, steps begin and vary in height from 0.23 m up to 0.98 m. The first steps are exposed to a high velocity flow from the gated control structure rather than the typical development seen with a free-overflow crest (Chanson [2006]). The specific discharges at design and maximum flow are 74 m^2/s and 172 m^2/s respectively.

Prior studies that have addressed cavitation potential on stepped spillways have proposed conservative approaches to design. Researchers have generally recommended that specific discharges be limited to around 30 m^2/s based on velocity and pressure field measurements. Early on, Frizell and Mefford [1991] downplayed the risk of cavitation damage on stepped chutes countering that the uniformly rough surface would likely have less potential for cavitation than an isolated roughness of the same geometry and Chanson [2001] added that the energy dissipation and aeration characteristics in general lead to lower velocities and deeper flows, thus lower cavitation potential. Matos et.al. [2000] formulated a process to evaluate cavitation potential based on friction factors and a theory introduced in Arndt and Ippen [1968] regarding cavitation inception on uniformly rough boundaries. Boes and Hager [2003] in their classic paper on the hydraulic design of stepped spillways also discounted the effect of subatmospheric pressures on the steps due to lower velocities and high amounts of air entrainment. Pfister et.al. [2006] first suggested the use of bottom aeration ramps for stepped chutes as a means to bypass the limitations on specific discharge; they assumed the critical cavitation index was represented by the characteristics of a single step ($\sigma_c \sim 1$). Gomes [2006] and Amador et.al. [2009] both completed work describing the hydrodynamic pressure field on stepped chutes and how the step pressure could affect the development of cavitation. They recommended an even smaller unit discharge (11 – 15 m^2/s) based on the measurement of negative pressures and large pressure fluctuations in the vicinity of the point of inception of air entrainment, predicting that cavitation may be possible in the unaerated portion of the flow.

The current studies are aimed at determining the critical cavitation index of a stepped chute and to provide enhanced design criteria for stepped chutes regarding prediction of the cavitation potential and new insights on possible damage.

2. LABORATORY STUDIES

Lab studies of a sectional stepped spillway chute were conducted at the Bureau of Reclamation's hydraulic laboratory, part of the Technical Service Center located in Denver, Colorado, USA. The model was a closed conduit acrylic channel with anodized aluminium steps placed along the bottom of the channel. Steps that were tested included two slopes, 1V:2.48H and 2.48V:1H and one roughness height of k=50 mm. Tests were performed at atmospheric conditions on the laboratory floor where overall pressure gradient and detailed particle image velocimetry (PIV) were performed. Flow rates were increased from 0.057 m^3/s up to 0.255 m^3/s in increments of 0.028 m^3/s. This same acrylic channel was then placed within the laboratory's low ambient pressure chamber (LAPC) where similar flow rates were tested at a reduced ambient pressure of 0.08 atm. These reduced pressure tests allowed for the observation of cavitation formation through the use of a high-speed video camera filming at 2000 frame/s.

2.1. Floor model at atmospheric pressure

The floor model consisted of a pressure tank leading to an acrylic sectional channel with the steps placed along the floor of the channel, figure 1. Overall pressure gradient was measured with piezometers and a manometer board. A particle image velocimetry (PIV) system manufactured by DANTEC Dynamics was used to capture 2-dimensional velocity fields near the conduit centerline at three step locations along the conduit, roughly beginning, mid, and end. PIV measurements used 100 image pairs, acquired at about 8 Hz to define the conditions at each location and flow rate. The laser was mounted above the channel, allowing a planar sheet of illumination to be projected though the clear acrylic lid and then imaged (photographed) through the clear side windows. The camera position was adjusted to allow imaging of the entire height of the test section and a width slightly more than one of the steps.

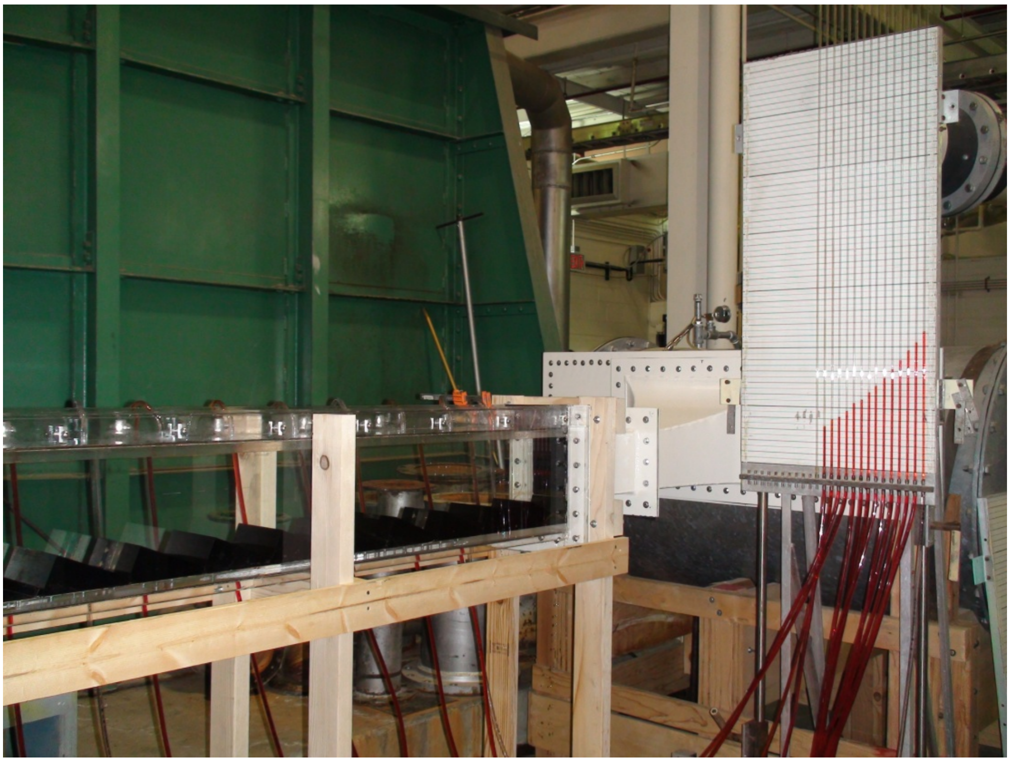


Figure 1 Acrylic channel with steps on invert. Channel is horizontal with steps placed to simulate slope of spillway. Piezometer tubes at right indicate pressure gradient along channel.

2.2. Reduced pressure model in the LAPC

The acrylic conduit with steps and the pressure tank transition were moved into the low ambient pressure chamber (LAPC) after the pressure and velocity data were collected. The LAPC is a permanent facility within the hydraulic laboratory that can operate a model at a reduced ambient pressure to allow for testing the model at low values of the cavitation parameter without the very high velocities that are typically characteristic of cavitation. Equation 1 shows the cavitation parameter (a modified Euler Number),

$$\sigma = \frac{2(P_o - P_v)}{\rho V_o^2} \qquad 1$$

where σ is the cavitation parameter, P_o is the reference pressure, P_v is the vapor pressure of water, ρ is the density of water, and V_o is the reference velocity. Figure 2 shows a view of the LAPC with the acrylic conduit in place.

This facility uses permanently installed instrumentation to measure discharge (electromagnetic flowmeter) and ambient pressure within the chamber. The local atmospheric pressure is measured adjacent to the facility using a NovaLynx Model 230-7410 Fortin-type barometer (accuracy ±0.25 mm-Hg). An acoustic emissions sensor was used to indicate cavitation activity. The AE sensor was a DECI Model SE9125-M, a mass-loaded transducer that is equally sensitive to both extensional and flexural waves and was attached to the outside of the conduit near the last steps. The signal conditioner was a DECI AE1000 and allowed sampling of the signal in two different bandwidths of frequency, a low-frequency BW (20 kHz- 70 kHz), and a high-frequency BW (100 kHz – 1 MHz). The extensional and shear waves always appear in the high frequency bandpass and the flexural waves in the lower frequency bandpass. A counting technique was used to quantify the activity in each of these frequency bands by noting the occurrences of acoustic emission peaks greater than a 100 mV threshold within a 30 s time period.

Figure 2 Low ambient pressure chamber (LAPC). A self-contained, recirculating flow chamber, capable of applying a reduced pressure of up to 0.08 atm to an entire model.

The cavitation parameter was calculated using a reference velocity equal to the mean velocity within the test section calculated by $V_o = Q/A$, where Q was the measured discharge and A was the area of flow (above the pseudo-bottom), and the reference pressure was from pressure gradient measurements taken on the lab floor at the most downstream step. This pressure decreased along the test section, yielding the lowest values of the Euler number at the downstream end of the conduit. High-speed video was collected using a Vision Research Inc. Phantom v4.2 digital camera and associated software. A macro/zoom lens allowed close up imaging from outside the chamber through the acrylic windows. All videos were collected at a rate of 2000 frame/s, and replayed at much slower rates in order to visualize the details of cavitation formation and progression. Still images were captured from the video clips.

3. RESULTS

This paper will focus on the reduced pressure testing that was performed in the LAPC. Some examples of the data taken on the laboratory floor will be presented as supporting information for the cavitation studies.

3.1. Reduced ambient pressure tests in the LAPC

The AE counts in a 30 s period were plotted versus the cavitation parameter for each of the basic conditions tested, figure 3. The critical values are typically noted by a change in slope – or more specifically a marked change in the rate of AE activity. Past studies have used other methods to “detect” cavitation in flowing systems, dynamic pressure fluctuations (flush-mounted transducer), sound pressure waves (hydrophone), and high frequency vibrations (accelerometer). The use of acoustic emissions has been used and proven as a successful method to detect cavitation in hydro turbines and has been shown to be very sensitive.

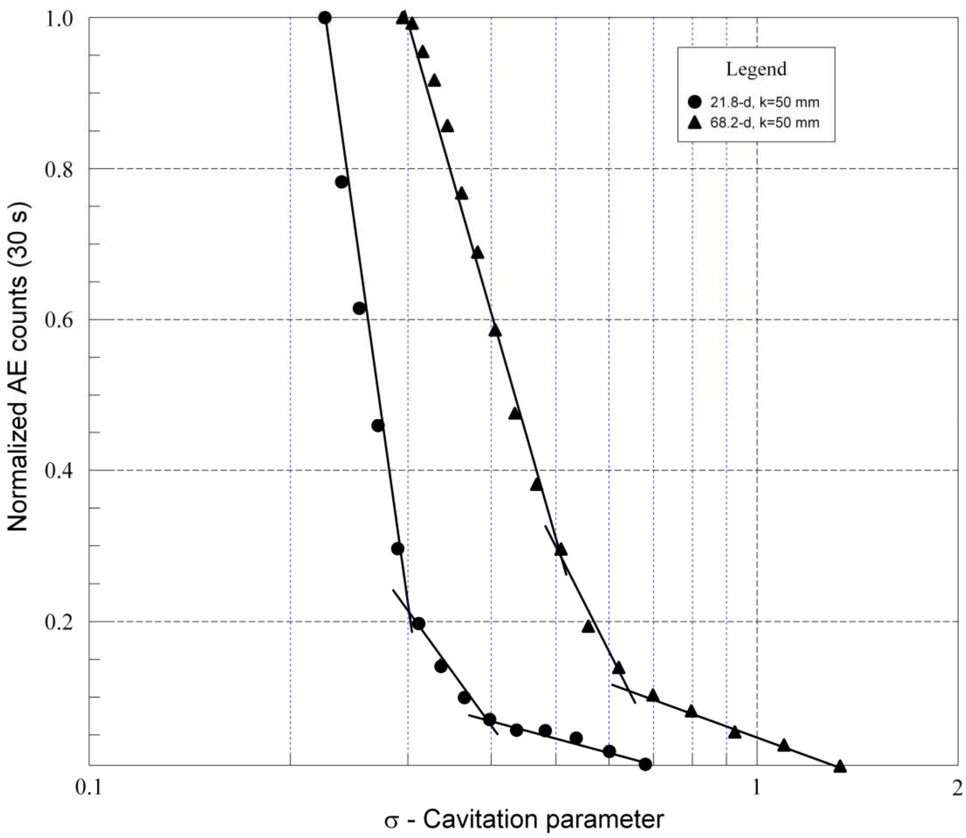


Figure 3 AE counts versus flow sigma for 2 slopes and roughness k=50 mm.

The development of the cavitation can be shown in Figure 4 in two pairs of photographs captured from the high-speed video. The photo pair shows the step riser and the step tread from the same step, with the successive pair representing a decreasing sigma value. With the steps reversed, a slope of 2.48 was simulated. Figure 5 shows progression of the cavitation with reducing sigma. Photo orientation is such that the step treads are in the horizontal; however the model arrangement was identical to the mild sloped case (flow horizontal and parallel to the pseudo-bottom).

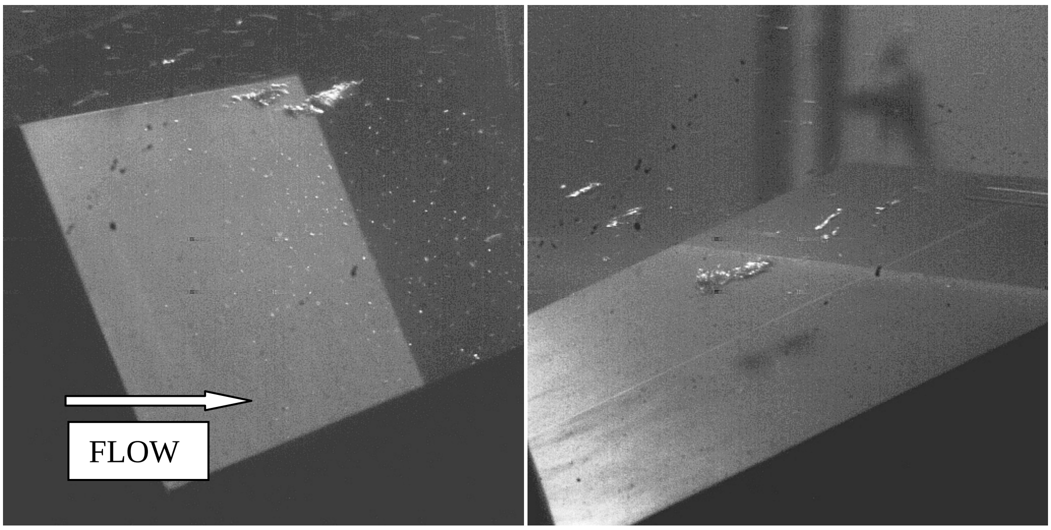


Figure 4a Cavitation on a 0.4025 slope, k= 50 mm, $\sigma =$ 0.68, left is riser, right is tread.

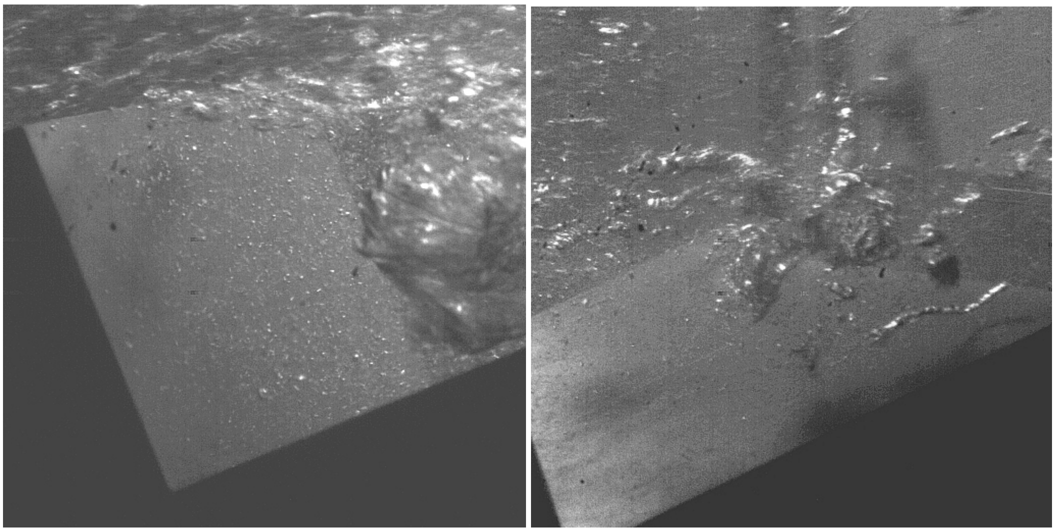
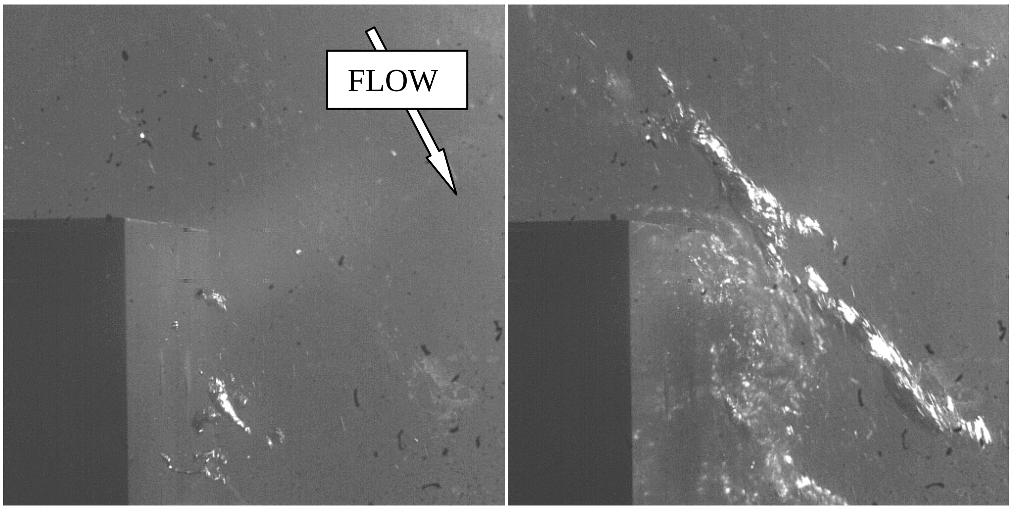


Figure 4b Cavitation further developed, slope = 0.4025, k=50mm. σ = 0.31.



σ = 1.33 σ = 0.56

Figure 5 Images from high-speed video of steps at 68.2-degrees and k = 50 mm. Orientation such that step tread is horizontal.

4. DISCUSSION

Results from reduced atmospheric testing of stepped channels of two slopes have shown that cavitation formation is indeed possible in the absence of aeration. A mild slope of 1V:2.48H (Folsom Dam auxiliary spillway) revealed cavitation beginning in the shear layer along a line defined as the pseudo-bottom (line connecting the individual step tips) at a flow sigma between 0.6 and 0.7. As the cavitation parameter was lowered, there was increased bubble cavitation at the tips of the steps. PIV measurements show the high levels of shear strain and vorticity and large turbulent energy production along the pseudo-bottom, figures 6 and 7. In particular, figure 6 on the left shows the high shear strain level along the pseudo-bottom, in the region where the streamwise vortices and stretched cavitation bubbles appear in figure 4. On the right side, the highest levels of turbulent kinetic energy exchange occurs along the pseudo-bottom, consistent with the findings of Amador, et al, [2006].

In figure 7, similar trends exist but the flow field is quite different from the mild slope. The mild slope has an impact zone about 2/3rd down the length of the tread while the steep slope features a recirculation zone that fills the cavity between adjacent step tips. Pressure gradient measurements revealed different friction losses for the two slopes tested along with the observed visual differences in cavitation characteristics. Cavitation began on the steep slope in the low pressure region just below the step tip on the vertical riser face, the area that Amador et.al. [2009] have reported extreme low pressures. Cavitation inception occurred at a value of the cavitation parameter around 1.3. As the cavitation developed, increased attached bubble cavitation on the step tips was observed, however streamwise vortex cavitation within the shear layer above the steps was also present. In figure 7, the rate of shear strain appears slightly less in magnitude but shows the same trends as the flatter slope. The turbulent energy production is an order of magnitude larger with a consistent defined layer along the pseudo-bottom.

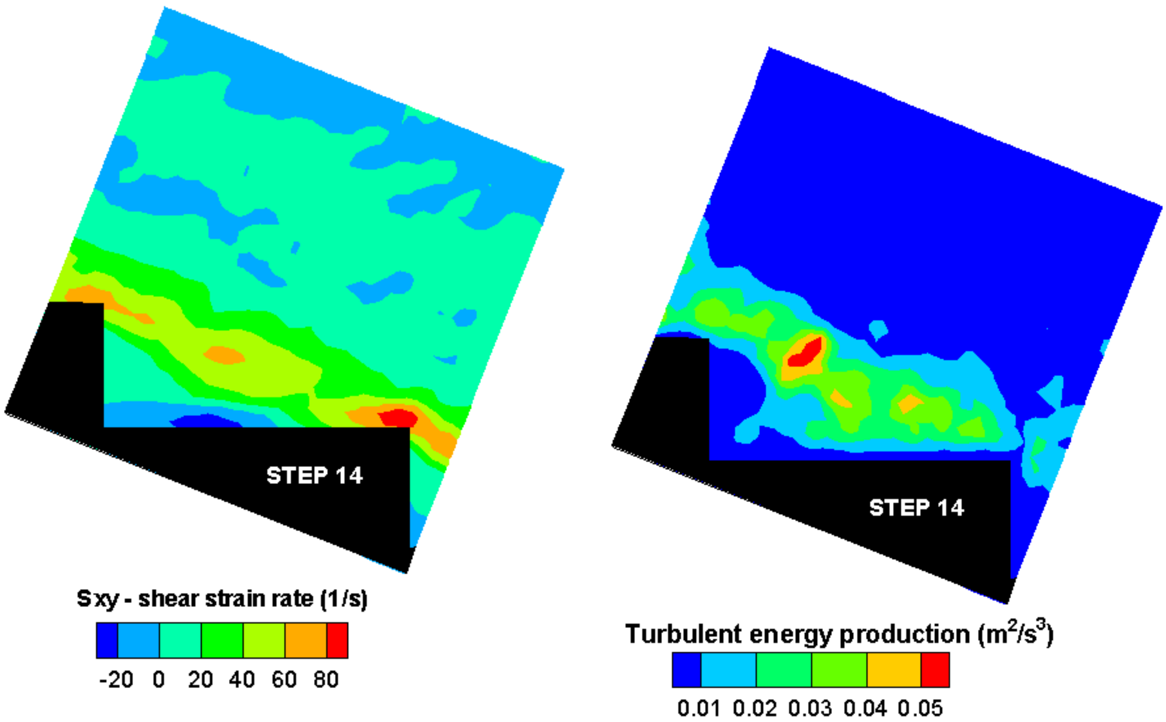


Figure 6 Data collected by PIV at a mean streamwise velocity of 3.78 m/s, slope 0.4025, k=50 mm. Rate of shear strain (left), turbulent energy production (right).

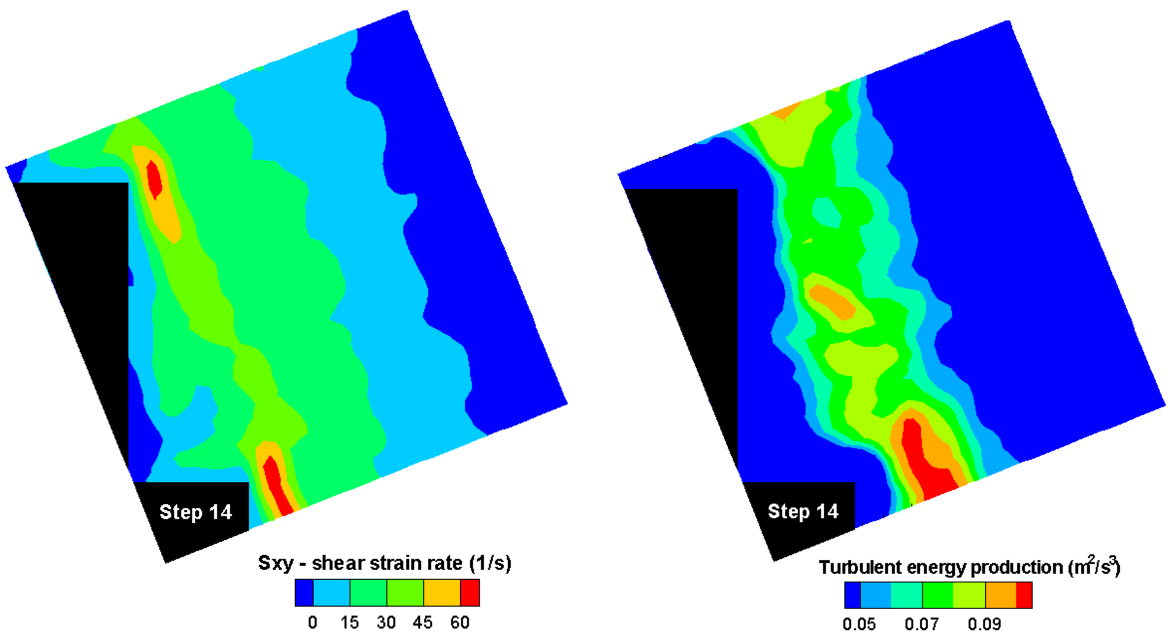


Figure 7 Data collected by PIV at a mean streamwise velocity of 3.78 m/s, slope 2.48, k=50 mm. Rate of shear strain (left), turbulent energy production (right).

Most likely, the uniformly distributed macro-roughness elements that make up the stepped chutes in the present study have features of both a rough surface boundary layer and a free shear flow. Arndt and Ippen [1968] proposed a universal law for the dependence of a critical cavitation index on the friction coefficient C_f. This linear relationship seemed to explain both boundary layer flows on smooth and roughened surfaces as well as in the free shear flows of jets and wakes. Preliminary results indicate that stepped spillways may also follow this trend.

As with most measurements in cavitating flows, there are difficulties due to many effects related to scaling of size and time and with water quality. Water with a lower tensile strength has been shown to cavitate prior to higher strength water for the same condition. This effect is due to the nuclei concentration, size, and distribution and is extremely important when studying cavitation on streamlined bodies; however it becomes less important in separated flows and free shear layers. The use of the LAPC to study hydraulic structures has been well accepted when used to model features with separated flows.

In the future, studies showing the effect of relative roughness and the damage potential of these complex cavitating flows will be presented.

5. ACKNOWLEDGMENTS

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